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Notes

Vol. I No. 2

STEADY-STATE ERROR CONSIDERATIONS, SINGLE-ENDED INVERTING AMPLIFIER

In the first issue of "Nexus Notes" we explained how the operational amplifier forces a null at the "summing point." Life would be pleasant indeed if this null were perfect. Unfortunately, this is not the case. Every amplifier however well designed and made will introduce errors. We will describe some of these errors and explain how to predict their effects on performance.

A practical operational amplifier has the following sources of error:

1. Input voltage offset
2. Input current offset
3. Gain variations
4. Loop dynamics.

The input offset voltage and current errors are in general d-c errors which vary with time, operating temperature and power supply changes. The effect of these errors on overall closed-loop circuit performance depends on the magnitude of the external input and feedback resistors, R_g and R_f, referring to Fig. 1.

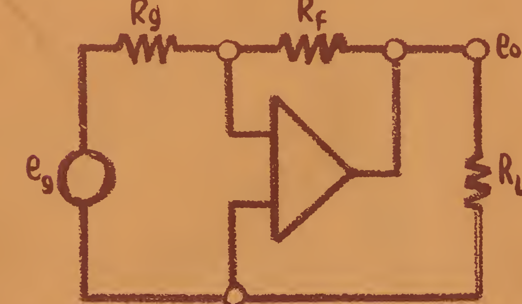
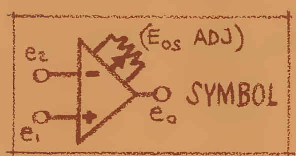


Fig. 1

The gain at low frequencies is affected by loading of the amplifier as well as time and variations in temperature and supply voltage. We will leave a discussion of loop-dynamic errors for a later issue of "Nexus Notes."

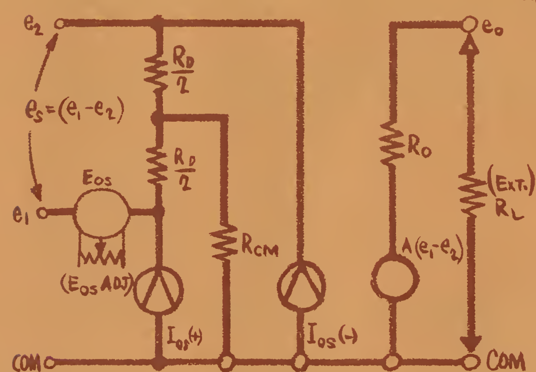
In order to obtain insight into the effects of these errors, we introduce an equivalent circuit (greatly simplified) in Fig. 2., which can represent the low frequency steady-state operational amplifier, if we can assume that there are no loop-dynamic problems.

OPEN LOOP LOW FREQUENCY EQUIVALENT CIRCUIT OF DIFFERENTIAL OPERATIONAL AMPLIFIER



$$e_o = A_o\,(e_1 - e_2)$$

WHERE $A_o = A\left(\frac{1}{1+\frac{R_o}{R_L}}\right)$



WHERE
- R_D = DIFFERENTIAL INPUT RESISTANCE, OPEN LOOP
- R_{CM} = COMMON MODE INPUT RESISTANCE, OPEN LOOP
- R_o = OUTPUT RESISTANCE, OPEN LOOP
- R_L = EXTERNAL LOAD RESISTANCE
- A = INTRINSIC LOW FREQUENCY AMPLIFICATION FACTOR
- A_o = OPEN LOOP GAIN UNDER ACTUAL LOAD CONDITIONS.
- E_{os} = OFFSET VOLTAGE REFERRED TO INPUT
- $I_{os}(-)$ = OFFSET CURRENT REFERRED TO INVERTING INPUT
- $I_{os}(+)$ = OFFSET CURRENT REFERRED TO NON-INVERTING (REFERENCE) INPUT.

Fig. 2

Since we are only treating the single-ended inverting case, we can simplify the equivalent circuit even more as shown in Fig. 3. Here we introduce the closed-loop input; feedback; and load resistors, R_g, R_f, and R_L, which we showed in Fig. 1.

CLOSED-LOOP SIMPLIFIED LOW FREQUENCY EQUIVALENT CIRCUIT SINGLE ENDED INVERTING OPERATIONAL AMPLIFIER

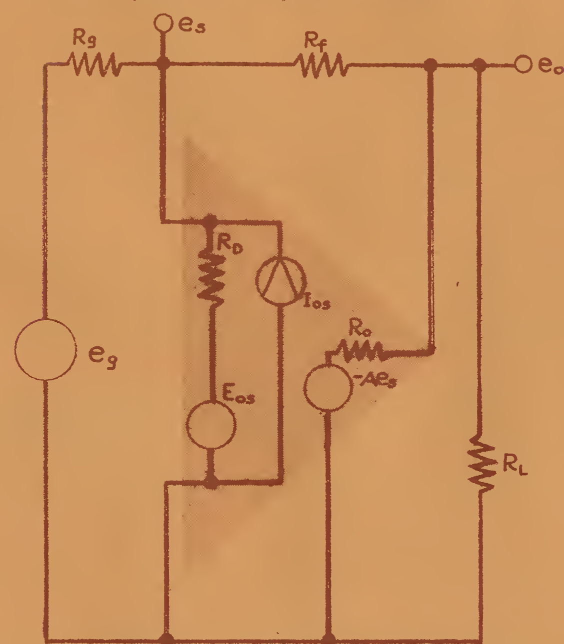


Fig. 3

Remembering that the amplifier endeavors to keep the voltage at the summing point near zero ("Nexus Notes" Vol. I No. 1) allows us to treat the errors introduced by offset voltage and offset current separately. For example,

1. Assume that we adjust E_{os} to zero and that temperature and power supply voltages are constant. Then, since we have no error voltage across R_g, there can be no error current flow in R_g. Therefore, the input offset current (I_{os}) will flow in R_f only, and the amplifier will offset the <u>output</u> voltage of the amount $I_{os}R_f$.

2. Assume that we reduce I_{os} to zero by some means, but that E_{os} is not zero. Now the amplifier's output will assume some value which classic feedback theory shows will be

$$E_o\,(\text{output offset error}) = \frac{E_{os}}{\beta}$$

where β is the feedback factor

$$\frac{R_{in}}{R_f + R_{in}}$$

and R_{in} is the parallel combination of R_g and R_D.

The factor $\frac{1}{\beta}$ is often referred to as "noise gain" (offset errors are the d-c component of noise), and points out the desirability of keeping $R_g < R_D$ to minimize the effects of variations in E_{os} on output voltage drift.

The output resistance causes the apparent open-loop gain, A_o, of the amplifier to be dependent on feedback and load resistances. This apparent gain is related to the intrinsic amplification factor, A, by

$$A_o = \frac{A}{1 + \frac{R_o}{R_{LL}}}$$

where R_{LL} is the parallel combination

$$\frac{R_L R_f}{R_L + R_f}$$

Some operational amplifiers are designed with a very high output impedance at low frequencies so that they are current sources. The voltage gain for these types is stated with a gain test load (R_t). For these types, loading changes the gain, A_o, by

$$\frac{R_{LL}}{R_t}$$

NEXUS® operational amplifiers have much lower current offset vs. temperature than competitive amplifiers, allowing the use of higher values of feedback and feedforward resistances.

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Phase / Gain / Frequency Plot of a Typical Operational Amplifier

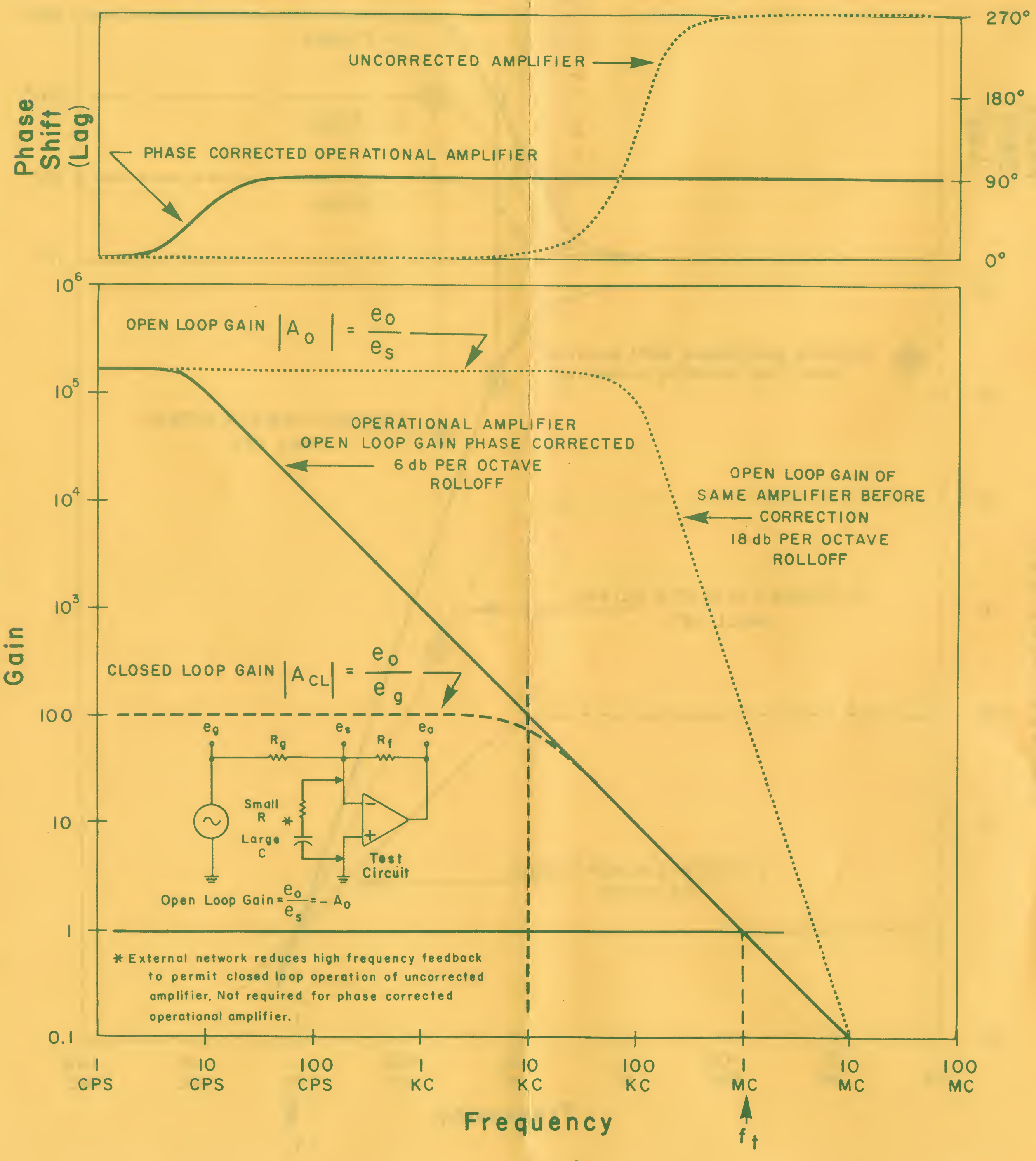

Fig. 3

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Notes

Vol. I No. 3

SMALL SIGNAL LOOP DYNAMICS OF OPERATIONAL AMPLIFIERS

Ideally, an operational amplifier would have zero phase shift and "flat" response over an infinite bandwidth. Like any real amplifier, however, operational amplifiers are subject to physical laws which determine that the open loop gain must fall off at high frequencies. An understanding of the why and wherefore of the high frequency behavior is a great aid to the user of operational amplifiers, and the insight which comes from assimilating the broad aspects of feedback theory helps the user avoid application designs which lead to loop instability and other problems.

Classical amplifier theory shows that any amplifier composed of a cascade of "minimum phase shift" stages (in which the high frequency falloff is determined by a single R-C time constant per stage) will show a gain at any frequency which is the product of the gains of individual stages and a phase shift at any frequency which is the sum of the phase shifts of individual stages.

As an example, consider the three-stage amplifier which is symbolically represented in Fig. 1.

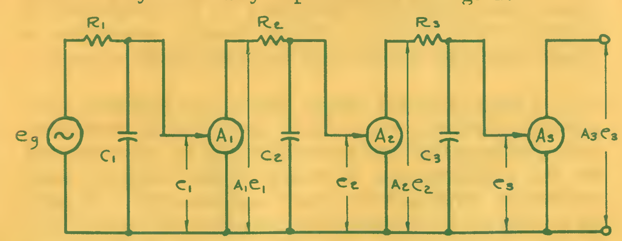

Fig. 1

The circular symbols  represent ideal amplifying devices with infinite inherent bandwidth and zero phase shift, and the series-shunt R-C's represent minimum phase shift time constants which cause the high frequencies to "roll off".

Fig. 2 (inside) shows the effect of cascading three identical amplifiers, each having a gain of 100 in the

"flat" region, via identical low pass filters for which $R_1C_1 = R_2C_2 = R_3C_3$. It can be seen that at a frequency of one megacycle the gain of one stage is unity, and since the overall gain is the product of the gain of the individual stages, the gain is also unity for two or three stages. This unity gain crossover point, f_t, is of great interest to feedback amplifier designs, as will be shown.

According to classical feedback theory, an amplifier will be unstable and oscillate at a frequency where the fed back (loop) gain is unity or greater and the phase of the fed back signal is 180°. Since a single stage of the amplifier shown in Fig. 1 exhibits a phase shift approaching 90° maximum, it can be seen that the entire output of such an amplifier can be applied to the input as inverse feedback. This is not true of the two-stage response because two minimum phase shift networks in cascade will yield almost 180° phase shift at finite frequencies. For this case only a small portion of the output signal could be applied as inverse feedback via a "flat" network without introducing distortions in the frequency or transient response. However, for three stages of amplification the phase shift passes through 180° and approaches 270° where the open loop gain is much greater than one, so that even less of the output may be utilized for feedback. The loop stability under this condition is, of course, very marginal, and oscillation may often be encountered under a wide range of feedback arrangements unless proper design precautions are observed. Since most users of operational amplifiers require both high gain and unconditional loop stability for any amount of feedback to assure computational accuracy and free choice of feedback networks, the design of a practical amplifier usually involves correcting the gain-phase-frequency relationship by means of certain internal "damping" networks. The most common technique used by operational amplifier designers is to synthesize a rolloff characteristic which closely simulates a single minimum phase shift network (6 db/octave).

Fig. 3 (see reverse) shows the phase and gain frequency response of a typical operational amplifier with phase correction networks built in, as compared to the performance it would exhibit without such networks. Although the open loop phase shift of such an amplifier is essentially a constant 90° except for very low frequencies, it can be seen that the closed loop characteristics are nevertheless essentially flat out to 10 kilocycles at a closed loop gain of 100. The product of closed loop gain vs. bandwidth (region of closed loop "flat" response) is often termed the small signal "gain-bandwidth product" of the amplifier, and is essentially the crossover-frequency, f_t. In this case, f_t is one megacycle, so a closed loop gain of 100 has a 10 kilocycle effective bandwidth, and a closed loop gain of 10 would have a 100 kilocycle bandwidth.

Phase/Gain/Frequency Plot of Multistage Amplifier

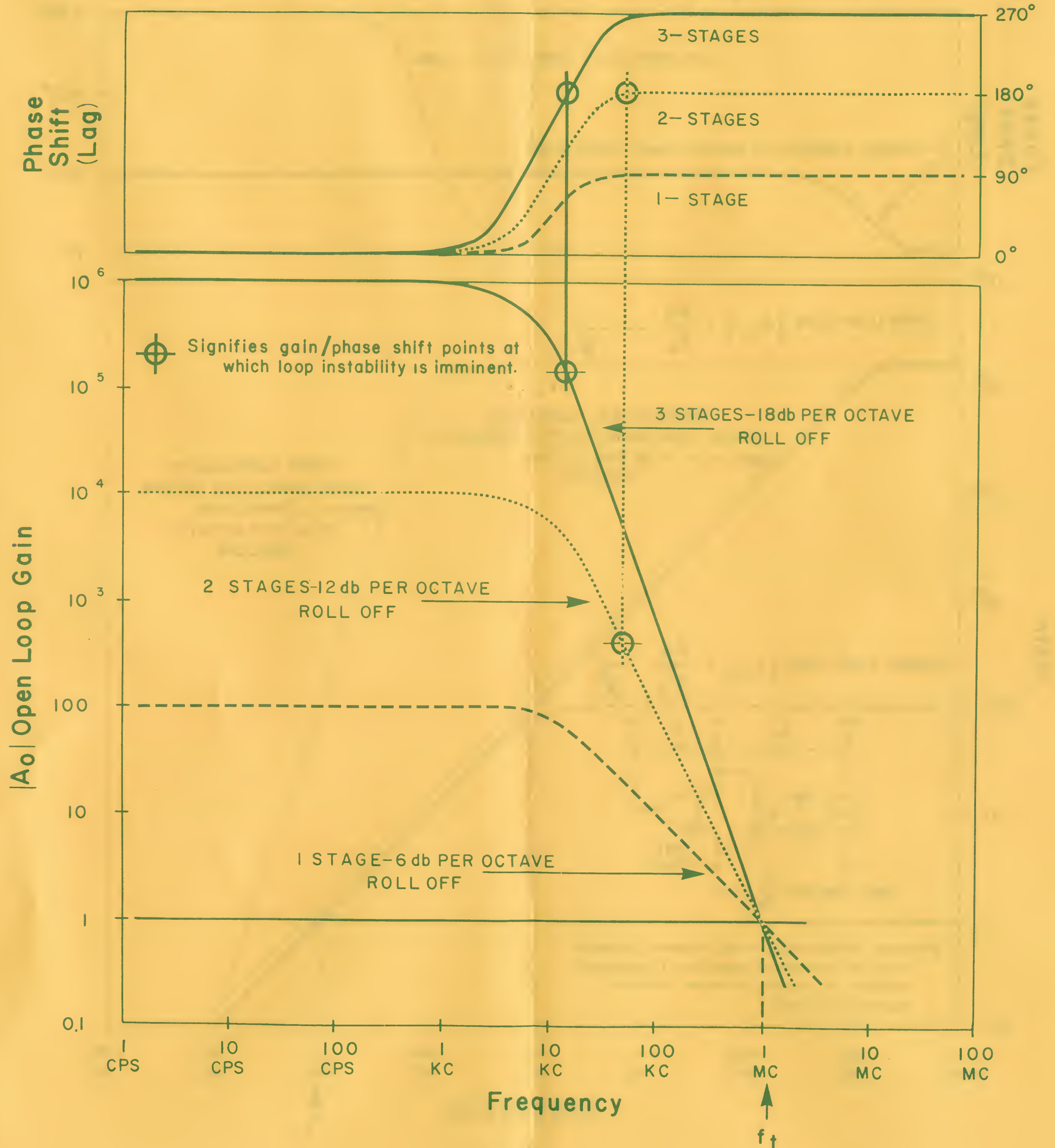

Fig. 2

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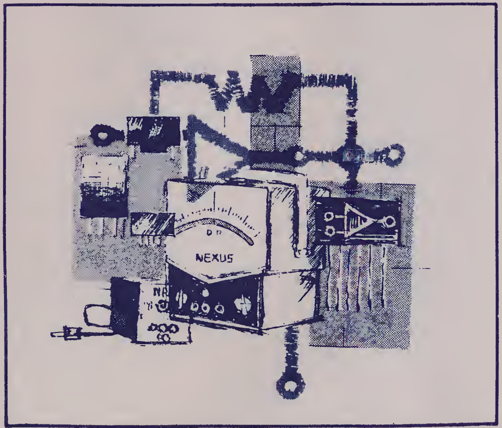
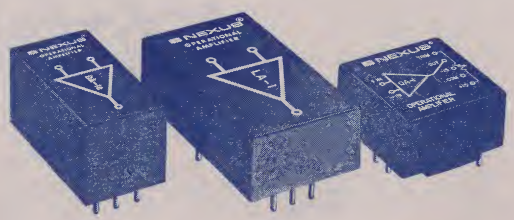
Vol. I No. 1

Early in 1962, Nexus was formed for the purpose of providing reliable d-c operational amplifiers, suitable for the most critical needs of process control, and low enough in cost to be considered for average use. Since Nexus is managed by engineering-oriented individuals who are well indoctrinated in the technology required to produce operational amplifiers and possess a thorough knowledge of the applications requirements for these devices, it has been possible for the company to take advantage of improvements in technology as they become available. The emphasis from the very beginning has been upon product and engineering excellence. Strict adherence to successful manufacturing techniques and proven quality control procedures has enabled Nexus to produce a wide range of products to satisfy the needs of the entire industry. Nexus believes that the assistance given to the customer in his application is as important as the quality of the product itself. Towards this end we present "Nexus Notes."



In addition to operational amplifiers, Nexus manufactures power supplies, logarithmic ratiometers and analog instruments.

In this first issue of "Nexus Notes" we will be extremely basic and describe the principals of the operational amplifier, and show why it is an indispensable tool to the modern process control engineer.

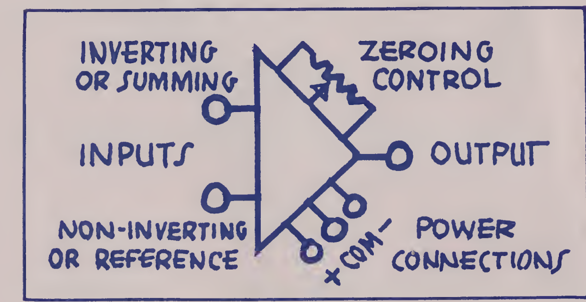


The nicest thing about an operational amplifier is the freedom of design which it affords the user. Think how nice it would be if you could predict the performance of a system using only the voltage developed across a passive element by a known current flowing in this element, and using the voltage to do whatever you want without loading errors, etc. The operational amplifier allows you to do this and in general to predict performance to accuracies limited only by the passive components.

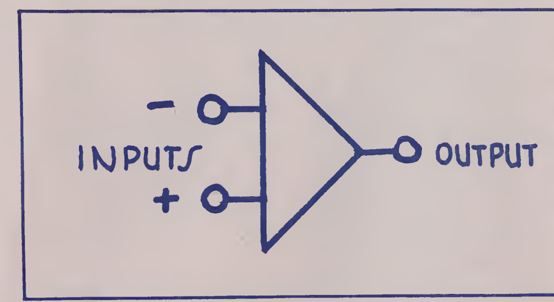
The operational amplifier in its most familiar form is a high gain (10^4 or greater), d-c amplifier, usually differential, having a low input error voltage and current and adequate output voltage and current for the application. The amplifier is always used with very large negative feedback. The high gain of the amplifier forces the input, commonly called the summing point, to always be very close to zero. As a result, the output voltage is substantially the voltage appearing across the feedback network. Since the input voltage and current offsets in the amplifier itself are very small, the voltage across this feedback network is substantially a result of the current flow in the feedback network. Since the current in the feedback network is almost wholly the current fed into the amplifier summing point, the performance of the circuit can be predicted in terms of the current(s) fed into the amplifier and the characteristics of the feedback network. Because the amplifier gain is very high, loading of the amplifier will have only second order effects on the system accuracy. The designer has only to select an amplifier whose characteristics are such that the errors introduced by changes in its characteristics with time, temperature, loading, etc., are smaller than the errors which can be tolerated.

COMPLETE DIAGRAM OF AMPLIFIER CONNECTIONS

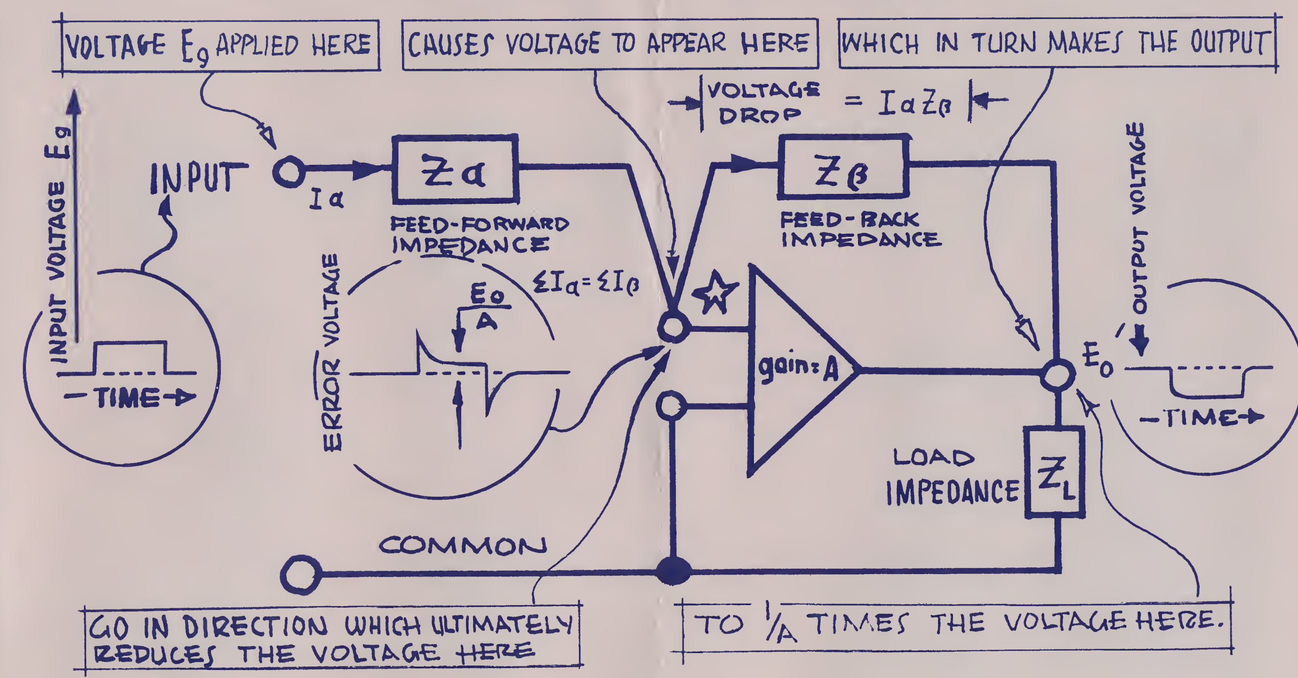
(ONLY USED ON FINAL DRAWINGS)



SHORTHAND SCHEMATIC



HOW IT WORKS



IF A IS VERY LARGE (AND USUALLY IS), AND $Z\alpha$ AND $Z\beta$ ARE REASONABLE IMPEDANCES, THEN ALL OF $I\alpha$ WILL FLOW IN $Z\beta$, AND E_{out} WILL BE ($I\alpha Z\beta$), (THE LOAD ONLY AFFECTS THE PERFORMANCE AS IT INFLUENCES A.) ☆ THE INVERTING INPUT IS CALLED THE "SUMMING POINT" BECAUSE HERE THE FEED FORWARD + FEEDBACK (AND ERROR) CURRENTS ARE SUMMED TO ZERO.

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Notes

Vol. I No. 4

THE SQ-10
OR
DOLLAR ENGINEERING

Although the intent of Nexus Notes is to provide technical assistance to users of operational amplifiers, we are deviating in this issue to describe the newest addition to the Nexus family. We feel justified in our choice of subject since we believe that the price of an operational amplifier is as important a consideration as any other specification.

The SQ-10 was specifically designed to fulfill the needs of the OEM market. The single unit price of $24 (much less in quantity), makes it uneconomical for the equipment designer to develop "in house" amplifiers of equivalent performance. Nexus, however, has achieved this low cost through large volume purchasing and production. The usual level of Nexus quality and reliability is rigidly maintained.

While the SQ-10 does not match the performance of higher priced Nexus amplifiers, it is equal in performance to many competitive types costing twice as much or more. A condensed table of electrical characteristics is included for your convenience.

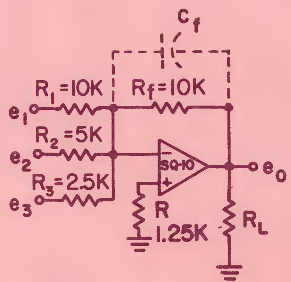
The applications shown are designed to yield accuracy of better than one per cent based on typical amplifier performance in the 25°C ± 10°C temperature range.

We hasten to add that only a few of the many uses for the SQ-10 have been indicated. Our Applications Engineering Department stands ready, as always, to offer assistance over the total spectrum of operational amplifier use.

Electrical Characteristics (Typical)

Supply Voltage:	±15 volts
Supply Current (@ full output):	±8 ma
Open-Loop Gain @ D. C.:	20K
Output Voltage Range:	±10 v @ 2 ma max.
I_{os} @ 25° C:	300 na
$\Delta I_{os} / \Delta T$ (-5° C to +70° C):	2 na/° C
$\Delta E_{os} / \Delta T$ (-5° C to +70° C):	20 μv/° C
f_t:	1.5 mc
Input Z:	0.1 meg. diff.
f_p:	20KC
Operating Temperature Range:	-25° C to +85° C
Case Size:	0. 58" (h) x 1.12" (l) x 1.12" (w)

ADDER

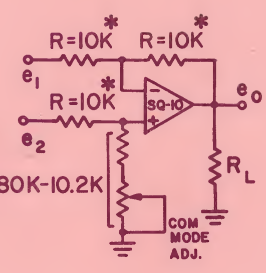


$$e_0 = -R_f\left[\frac{e_1}{R_1}+\frac{e_2}{R_2}+\frac{e_3}{R_3}\right]$$

$$= -\left[e_1 + 2e_2 + 4e_3\right]$$

R = R1 ll R2 ll R3 ll Rf

SUBTRACTOR

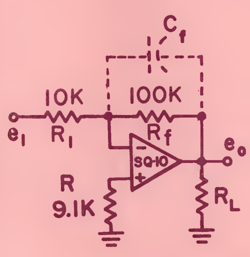


$e_2 \leq 6v$

$$e_0 = e_2 - e_1$$

* MATCHED RESISTORS

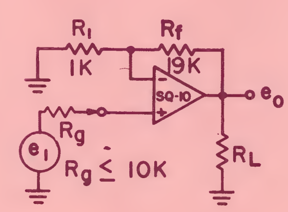
INVERTING AMPLIFIER



$$e_0 = -e_1\frac{R_f}{R_1} = -10e_1$$

R = R1 ll Rf

NON-INVERTING AMPLIFIER



$$e_0 = e_1\left[1 + \frac{R_f}{R_1}\right]$$

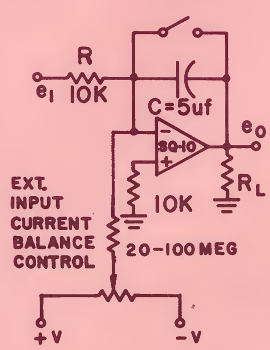
$$e_0 = 20e_1$$

$e_1 \leq 3v$

NOTE:

When Rf = 0 & R1 = ∞: $e_0 = e_1$

INTEGRATOR



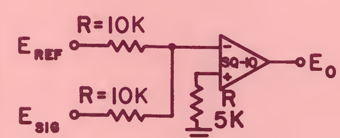
$e_1 = \geq 0.1V$; 0.1ms < t < 1 Sec

$$e_0 = -\frac{1}{RC}\int_0^t e_1\,dt$$

$$e_0 = -20\int_0^t e_1\,dt$$

NOTE: With e_1 a d.c. voltage, e_0 is an inverted ramp.

SIMPLEST VOLTAGE CROSSING DETECTOR



R = R1 ll R2

Eref−Esig > 0 e_0 = −10v
Eref−Esig = 0 e_0 = 0
Eref−Esig < 0 e_0 = +10v
Eref > 100mv < Esig
Rise time & fall time ~ 20μs